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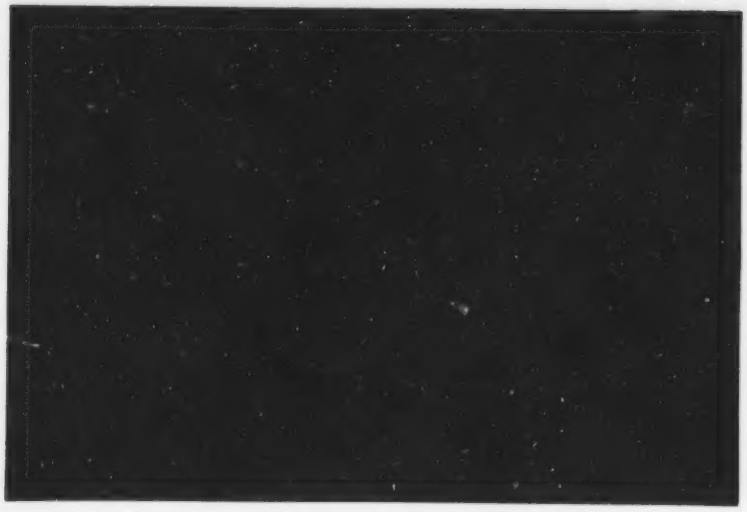

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CAPABILITY OF EMAT SYSTEM FOR STEEL CYLINDER FLAW DETECTION

Prepared for

Transportation Development Centre
Safety and Security
Transport Canada

November 1999

by

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16. Abstract

An electromagnetic acoustic transducer (EMAT)-ultrasonic guided wave inspection system, developed by Tektrend Inc. of Montreal, is currently being used for scanning the sidewall portions of industrial high-pressure gas cylinders. Unlike conventional ultrasonic scanning, the ultrasonic guided waves allow inspection of bends and hidden parts of cylindrical structures. The technology may therefore be adaptable to the inspection of cylinder ends, an area that cannot be easily inspected using ultrasonic scanning.

The ability of the EMAT-ultrasonic guided waves to detect crack-like defects in the sidewalls and ends of cylinders was investigated. Fatigue cracks were generated in the sidewalls of cylinders by hydraulic pressure cycling. The study included flaws in necks of cylinders that had been removed from service. These flaws had been detected by manual ultrasonic inspection.

The EMAT-ultrasonic guided wave method had limited success in detecting fatigue cracks in the sidewalls of the cylinders, and could not detect the neck flaw in another cylinder. The detection problem can likely be attributed to the transducer orientation used for the introduction of the guided waves.

The research team recommended further development of the inspection technique before it could be applied to the detection of longitudinally oriented flaws in the ends of cylinders.

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16. Résumé

Un système d'inspection par transduction électromagnéto-acoustique (EMAT) à faisceau ultrasonore focalisé, étudié par la société Tektrend Inc., de Montréal, est mis à l'essai pour l'auscultation du corps des bouteilles de gaz sous pression industrielles. Contrairement à l'auscultation ultrasonore classique, cette nouvelle technique permet d'examiner les bouteilles cylindriques aux angles et dans les parties jusqu'ici inaccessibles. En d'autres termes, elle pourra servir à inspecter les bouts des bouteilles, un endroit difficile à ausculter par la technique ultrasonore classique.

Les chercheurs ont étudié l'aptitude du nouveau système EMAT à faisceau ultrasonore focalisé à détecter les fissures dans le corps et les bouts des bouteilles. Le corps des bouteilles auscultées comportait des fissures de fatigue engendrées par variation cyclique d'une charge hydraulique. Les essais de détection ont également visé le col de bouteilles retirées du service dont on savait qu'elles comportaient des fissures grâce à une auscultation ultrasonore classique.

La technique EMAT à faisceau ultrasonore focalisé a affiché un faible taux de réussite quant à la détection des fissures de fatigue dans le corps des bouteilles et elle s'est avérée incapable de détecter le défaut que présentait le col d'une autre bouteille. Les difficultés de détection sont sans doute attribuables à l'orientation du transducteur utilisé pour l'émission du faisceau ultrasonore focalisé.

L'équipe de recherche a recommandé de pousser plus avant le développement de la technique avant de vérifier son aptitude à détecter les fissures longitudinales dans les bouts des bouteilles.

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EXECUTIVE SUMMARY

High-pressure steel gas cylinders used for the storage of compressed natural gas (CNG) as a vehicle fuel are currently being non-destructively inspected using conventional ultrasonic scanning techniques. The cylinder sidewalls are scanned using an automated system, while the changing contours of the cylinder ends require the use of manual ultrasonic inspection. The manual portion of the inspection increases the time and cost of inspection, and relies on human skills of observation and interpretation of indications.

Tektrend Inc. of Montreal has developed a method of ultrasonic guided wave inspection using electromagnetic acoustic transducer (EMAT) technology for the inspection of steel high-pressure cylinders used for industrial gas service. Automated systems for the inspection of cylinder sidewalls are commercially available. Unlike conventional ultrasonic scanning, the guided waves allow inspection of bends and hidden parts of cylindrical structures. It may therefore be possible to adapt this technology for the automated inspection of CNG cylinder ends.

A program to evaluate the ability of the EMAT-ultrasonic guided waves to detect crack-like defects was initiated. Testing was performed on cylinders with marked service pressures of either 3,600 psi or 4,000 psi, used for the ground storage of CNG at filling stations. Powertech Labs used conventional ultrasonic inspection methods to identify ground storage cylinders with flaws in either the sidewall or end regions. Typically, the flaws oriented in the longitudinal (axial) direction along the length of the cylinder, as a result of the cylinder manufacturing process.

Several of the flawed cylinders were hydraulically pressure cycled in the approximate range of 10 percent to 125 percent of service pressure in an attempt to increase the size of the flaws by initiating the growth of fatigue cracks. The pressure cycling had limited success in increasing the initial flaw size, since a fatigue crack would often initiate elsewhere on the internal sidewall surface and grow through-wall. The flawed cylinders, along with several calibration samples containing machined flaws, were supplied to Tektrend Inc. for evaluation using the EMAT-ultrasonic guided wave system.

As reported by Tektrend, the EMAT-ultrasonic guided wave method apparently had only limited success in detecting the longitudinally oriented fatigue cracks in the sidewalls of the cylinders. The method also could not detect the longitudinally oriented flaws in the neck ends of cylinders. It was suspected that the EMAT transducer orientation (longitudinal versus transverse) contributed to the detection problem.

Further development would be required before the inspection technique could be applied to the detection of longitudinally oriented flaws in the ends of cylinders.

SOMMAIRE

L'inspection des bouteilles en acier servant au stockage haute pression de gaz naturel comprimé à bord de véhicules mus par ce combustible se fait à l'heure actuelle selon une technique éprouvée de contrôle non destructif aux ultrasons. L'auscultation ultrasonore des bouteilles se fait au moyen d'un dispositif automatisé, mais le contrôle des bouts à courbure variable n'est possible qu'à l'aide d'un système manuel. La partie manuelle de l'inspection est onéreuse en temps et en argent et ses résultats sont largement tributaires de la compétence sur le plan de l'observation et de l'interprétation des lectures.

La société Tektrend Inc., de Montréal, a étudié une technique d'auscultation ultrasonore à faisceau focalisé dérivée de la technologie de la transduction électromagnéto-acoustique (EMAT pour electromagnetic acoustic transducer) et applicable à l'inspection des bouteilles en acier servant au stockage haute pression de gaz industriels. Il existe déjà sur le marché des systèmes automatisés d'inspection du corps des bouteilles, mais la technique à faisceau focalisé présente par rapport à la méthode classique d'auscultation ultrasonore l'avantage de permettre l'inspection des bouteilles aux angles et dans les endroits jusqu'ici inaccessibles. Et il est peut-être possible d'adapter cette technologie à l'inspection automatisée des bouts des bouteilles de GNC.

Aussi a-t-on entrepris un programme visant à évaluer l'aptitude de la technique d'inspection par transduction électromagnéto-acoustique (EMAT) à faisceau ultrasonore focalisé à détecter les fissures dans les bouteilles de gaz naturel. Les essais ont été réalisés sur des bouteilles à pression de service nominale de 3 600 lb/po^2 ou de 4 000 lb/po^2, utilisées pour le stockage de GNC dans les stations-service. Powertech Labs s'est servie de techniques classiques d'auscultation ultrasonore pour repérer des bouteilles dont le corps ou les bouts comportaient des fissures. De façon générale, les fissures détectées avaient une orientation longitudinale, c'est-à-dire généralement parallèle à l'axe longitudinal de la bouteille, qui peut être reliée au procédé de fabrication des bouteilles.

Powertech Labs a soumis plusieurs de ces bouteilles à une variation cyclique de charge hydraulique entre environ 10 et 125 pour cent de la pression de service afin d'agrandir les défauts existants par amorce de fissures de fatigue. Cette méthode n'a pas donné les résultats escomptés puisque, plutôt que d'agrandir le défaut existant, elle donnait souvent lieu à une fissuration par fatigue ailleurs sur la face intérieure du corps, la fissure de fatigue se propageant sur toute l'épaisseur de la paroi. Les bouteilles affaiblies ainsi que plusieurs éprouvettes d'étalonnage comportant des défauts usinés ont été remises à Tektrend Inc. pour les fins de l'évaluation de la technique de détection électromagnéto-acoustique (EMAT) à faisceau ultrasonore focalisé.

Selon le rapport fourni par Tektrend, la technique EMAT à faisceau ultrasonore focalisé a affiché un faible taux de réussite quant à la détection des fissures de fatigue longitudinales dans le corps des bouteilles et elle s'est avérée incapable de détecter les fissures longitudinales dans le col des bouteilles. Les chercheurs pensent que les difficultés de

détection peuvent être liées à l'orientation (longitudinale plutôt que transversale) du transducteur utilisé pour l'émission du faisceau ultrasonore focalisé.

D'autres travaux de recherche seraient nécessaires avant que cette technique d'inspection puisse servir à la détection des fissures longitudinales dans les bouts des bouteilles.

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A Description of the EMAT System of Guided Waves

B Non-Destructive Evaluation of Compresses Gas Cylinders Using Guided Waves and EMATs

1. BACKGROUND

High pressure cylinders used for the transportation of compressed gas typically require a periodic retest using hydrostatic pressure. For steel and aluminum cylinders, ultrasonic scanning has recently been introduced in several countries as an alternative retest method. While hydrostatic testing can provide an indication of gross defects in cylinders, ultrasonic inspection has the ability to detect defects at an earlier stage of development. Many standards now require ultrasonic scanning of cylinder sidewalls during production, to ensure the absence of defects that could result in premature failure.

A limitation associated with the conventional ultrasonic C-scan inspection method is the difficulty in performing automated scanning of the cylinder ends. Automation is prevented by the difficulty in orienting the transducers to match the non-parallel contours of the inside and outside surfaces of cylinder ends. As a result, cylinder ends must be ultrasonically inspected manually, requiring considerable labour and time.

2. EMAT TECHNOLOGY

Electromagnetic Acoustic Transducers (EMATs) are ideal for the on-line inspection of steel structures, because they provide a noncontacting means for generating and detecting ultrasound in metals. EMAT technology has been adapted by Tektrend International Inc. to inspect the sidewalls of cylinders in a manner similar to that used by ultrasonic scanning systems. While not as accurate as ultrasonic measurements for defining relatively small defects, the guided waves generated by an EMAT system offer the capability of inspecting around bends in structures, such as the ends of cylinders. A description of the system is provided in Appendix A.

3. RESEARCH APPROACH

The ability of Tektrend's EMAT system to detect flaws in steel cylinders was evaluated by providing steel cylinders containing flaws in the sidewalls and the head region. The high pressure cylinders were of TC-3AAM design, measuring approximately 228 mm (9 inches) in diameter and 158 mm (62 inches) in length, with a water volume of 50 L.

In one cylinder, a neck flaw measuring about 5 percent of the wall thickness and 25 mm long was detected using manual ultrasonic inspection. The cylinder was then hydraulically pressure cycled from 10 percent of the service pressure up to 125 percent of the service pressure in an attempt to enlarge the pre-existing neck flaw. It was found that instead of enlarging the neck flaw, the pressure cycling caused a fatigue crack to develop in the cylinder sidewall.

Pressure cycling typically causes fatigue cracks to initiate on the internal surface of cylinders in the sidewall region. This happens because the hoop stresses in the sidewall of cylinder designs are significantly greater than the stresses existing in the dome ends of cylinders. The greater hoop stresses also result in the fatigue cracks being oriented in the axial (longitudinal) direction. Fatigue cracks only initiate in the neck or base portion of cylinders if there is a pre-existing flaw of significant size. The pre-existing neck flaw detected in the cylinder could not have been a fatigue crack initiated in service, otherwise it would have continued to grow during hydraulic pressure cycling. Instead the flaw must have been caused by pre-existing folds introduced during cylinder manufacture.

Several other cylinders were hydraulically pressure cycled to generate fatigue cracks. The following cylinders were then supplied to Tektrend for evaluation:

Serial Number	Service Pressure (psi)	Nature of Flaw
5848407	3,600	neck flaw of 5% depth and 25 mm length, also through-wall fatigue crack in sidewall
5980810	3,600	pressure cycled, but no leak occurred
6001583	4,000	through-wall fatigue crack in sidewall
6001607	4,000	no flaws

In addition, a cylinder neck end, containing machined neck flaws oriented in the axial direction, and a cylinder base end, containing machined flaws oriented in the circumferential direction, were provided for calibration purposes. The locations and types of flaws, if any, were not marked on the cylinders.

4. RESULTS

The results of inspecting the four cylinders using guided waves and EMAT are detailed in the TISEC/Tektrend report in Appendix B.

5. DISCUSSION

The report in Appendix B indicates that the EMAT probe unit was used to scan the cylinders in the longitudinal direction only. The EMAT system detected a sidewall flaw in cylinder s/n 5980810. This cylinder had been pressure cycled, but a through-wall fatigue crack had not been developed. Possibly the pressure cycling had created a smaller fatigue crack in the sidewall, but the exact nature of the defect detected by the EMAT system requires verification.

The EMAT system did not detect the through-wall fatigue cracks in the sidewalls of the other cylinders (cylinder s/n 6001583 and s/n 5848407). Since the through-wall fatigue cracks were oriented in the axial direction, it was likely that the cracks would avoid detection if the guided waves were only applied in the same direction during the scanning of the cylinders.

The EMAT system was also unable to detect the neck flaw on either the calibration standard (10% depth and 25 mm length), or on cylinder s/n 5848407. Again, this is probably because the neck flaws occur oriented in the axial direction, which is parallel to the direction of the guided waves used for scanning. Detection would probably require the EMAT transducers to be oriented to generate guided waves in the circumferential direction over the neck end of the cylinder.

6. CONCLUSIONS

Using the EMAT-ultrasonic guided wave method to scan in the circumferential direction such that the guided waves travel longitudinally along the cylinder limited its ability to detect the longitudinally oriented fatigue cracks in the sidewalls and necks of cylinders.

Further development of the inspection technique is required for it to be applied to the detection of flaws oriented longitudinally in the ends of cylinders.

7. RECOMMENDATIONS

Verify the nature of defects (if any) existing in cylinder s/n 5980810 by ultrasonic inspection.

Adapt the EMAT equipment to scan in the transverse direction on the ends of cylinders, and repeat the inspections.

APPENDIX A

Description of the EMAT System of Guided Waves

Applications focus on Cylinder Inspection

Several tests were conducted using guided waves on steel cylinders. These tests show that guided waves may be used as a fast, reliable and cost-effective inspection tool to locate and detect crack-like and wall thinning defects in steel cylinders.

Figure 1 shows the time response obtained from the S_o lamb mode using a pulse-echo arrangement. The time response shown in Figure 1a for a non-defected area of the cylinder shows only the S_o mode reflected approximately at 1200μs from the end of the specimen. Waves arriving before the S_o wave mode represent the excitation (main bang) and the reverberation produced in the interface between the transducer element and the plexiglas wedge. In Figure 1b, an additional wave packet corresponds to the reflection of the S_o mode from the crack which is observed. Existence of an additional packet of waveforms is strong evidence of the existence of a defect.

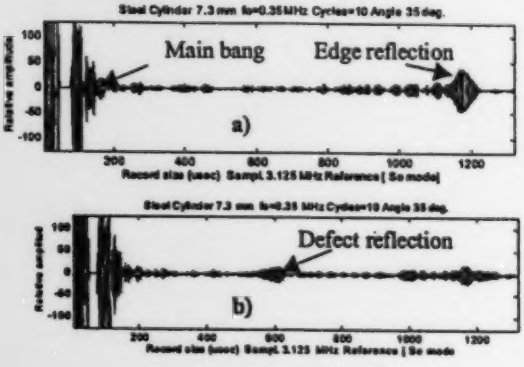

Figure 1. Guided Wave Results

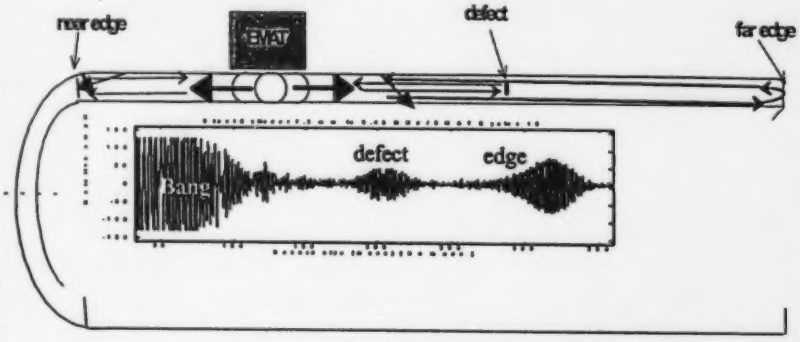

Figure 2. EMAT pulse-echo response for cylinder with a crack-like defect

Figure 2 shows the results obtained from inspection of th same cylinder with a previously detected defect using an EMAT probe to excite So wave mode in pulse-echo arrangement. Slight differences in the position of inspection probe and the interpretation of the results occurred because the EMATs transducer transmits in both directions

In Figure 2, the EMAT transducer is placed facing the defect resulting in an extra reflection of So time response. The first wave packet is the main bang exercised to excite the EMAT, the second wave packet represents a reflection produced from the defect while the third one is a reflectio from the near end of the cylinder.

Tests were continued on a half section cylinder whose ends were cut, giving a straight section 1000 mm long and sliced in the middle so that internal defects are easily introduced. The results in the following figures illustrate the detectability as well as the long-range inspection capability of the guided wave procedure. Figure 3 shows results from a crack-like defect detected 190 mm away from the EMAT transducer.

A number of tests were also carried out while the probe unit moved longitudinally to send its bea circumferentially perpendicular to the scan axis. Figure 4 shows the time response o So mode while using circumferentially pulse-echo approach to detect the same type of defects. Reflection of the So mode from the defect can now be clearly observed.

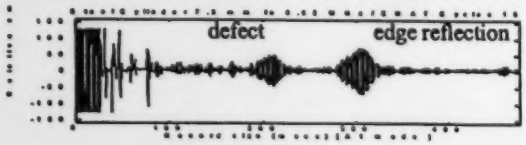

Figure 3. PE response for a steel cylinde

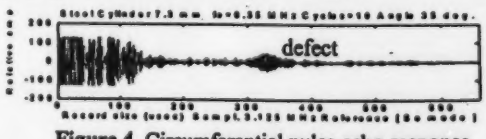

Figure 4. Circumferential pulse-echo response

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INSPECTION OF COMPRESSED GAS CYLINDERS USING ULTRASONIC GUIDED WAVES

Prepared by:

Tektrend International Inc
A. Chahbaz and M. Brassard

ABSTRACT

Mechanical integrity of cylindrical structures ranged from piping to storage and pressure vessels needs to be maintained at a high level to ensure safety and reliability. Current inspection techniques are less sensitive to common defects and unable to inspect bends and other insulated cylinders and cylindrical structures. This paper describes a novel automated inspection system based on EMAT-Ultrasonic guided wave method.

In this work, several test cases are conducted on steel cylinders with real and simulated defects. Contact-free EMAT probes were designed and mounted in the system. Results from the guided wave inspection technique demonstrated good detectability of defects in longitudinal and circumferential direction of the cylinders. Moreover, results from several real-time tests confirmed the guided wave inspection system as fast, reliable and cost effective inspection tool to locate and detect crack-like and wall thinning defects in compressed gas cylinders.

INTRODUCTION

Ultrasonic inspection is a very flexible method where several inspection modes are available. Ultrasonic methods detect all flaws in the path of the ultrasonic stress wave within the limits of sensitivity of the method.

In the conventional configuration, straight beam probes scan the cylindrical wall to measure wall thickness and detect lamination and (planar) defects in the plane of the wall. Angle-beam probes are used to detect the defects oriented normal to the plane of the wall.

Conventional ultrasonic C-scan can inspect the straight sectors of the cylinder but is not suited for inspection of bends and hidden parts of a cylindrical structure. Moreover, inspection of the cylinder with C-scan is very time consuming since a point-by-point measurement is needed for a complete inspection of the structure and difficulties in inspecting around bends, are disadvantages of conventional ultrasonics. However, ultrasonic measurements are more appropriate and precise for small defects.

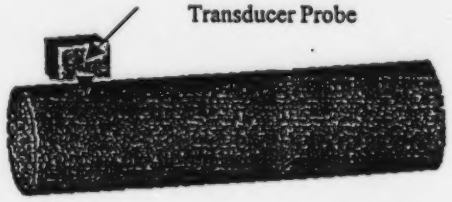


Figure 1 Scan of cylindrical structure

This work evaluates the ability of ultrasonic guided waves to detect several types of defects in cylindrical structures with different pre-selected wave modes. We also demonstrate ultrasonic guided wave method as an alternative to standard ultrasonic techniques and how to address their

deficiencies. This approach is based on the use of ultrasonic guided waves or, generally, the resonant modes of propagation in the cylindrical geometry.

GUIDED WAVE PROPAGATION IN CYLINDERS

Guided wave or more general resonant mode propagation in cylinders is complex due to it curved geometry where complex three-dimensional propagation of waves is produced. In addition, the attenuation mechanisms (and the anisotropic nature of the material in some cases) through the thickness of their material lead to various distortion phenomena. The resonant modes of an isotropic cylindrical structure have been extensively studied [1,2,3]. However, in this section, we will only explain how resonant modes are related to Lamb wave modes of an isotropic plate and whether this basic understanding is still useful in the presence of moderate curvature.

The problem of a hollow circular cylinder has been investigated in an exact formulation without any of the approximation usually associated with thin cylindrical shell theories [4,5]. Dispersion curves for all cylindrical shell modes also were derived; it was demonstrated that a subset of these modes is reducible to Lamb waves in the limit of small cylinder curvature (large radius) [6].

Generally, the resonant wave modes of cylindrical structure belong to two groups. The first group represents resonant wave modes propagating in the axial plane (axially symmetric modes) and the other group are modes propagating in the transverse plane of the cylindrical coordinate system (non-axially symmetric modes). Each group by itself can be divided further into two types of resonant modes. One type is unique to cylindrical geometry and the other type is equivalent to Lamb wave modes of the flat plate [7].

The two sets of resonant wave modes which are equivalent to Lamb waves are called the planar and axial modes. The planar modes propagate circumferentially and the axial ones along the cylinder. In this work, the axially symmetric modes equivalent to Lamb waves are used $L(0,m)(m=1,2,3...)$ where $L(0,1) \cong A_0$ and $L(0,2) \cong S_0$ ...

While standard ultrasonic waves propagate through the thickness of a cylinder walls, Lamb waves propagate along the walls and are introduced in it via two angled probes (or EMATs probes) making a global interrogation of the line joining the two probes. With Lamb wave propagation, the vibration patterns through the thickness of the cylinder in the axial and circumferential directions are quite different for different Lamb modes.

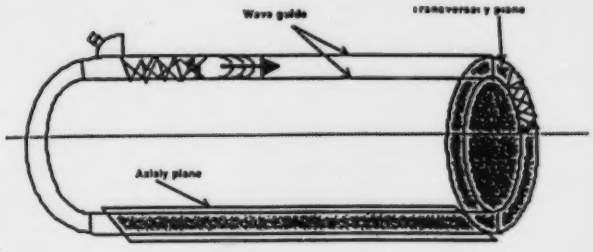


Figure 2 Guided Wave propagation in a cylindrical structure

They may also change for different frequencies. Thus, to demonstrate Lamb wave propagation in cylindrical structures, an initial experimental tests were carried out by measuring velocities in different axial and circumferential directions of propagation (parallel, perpendicular to simulated defects). Using the fundamental Lamb modes A_o and S_o, detection and interaction of Lamb waves modes with defects in cylindrical structures were also investigated. However, it was necessary to predict theoretical dispersion curves in order to verify the velocity of the pre-selected modes, to excite and choose at which point(s) on the dispersion curves these modes are to be excited. It was essential also to analyze wave structures to determine the most suitable mode for a certain application or defects [8].

In the following section results show a strong detectability of defects in the straight cylindrical section as well as the end sections; a reproducible response to different cylinders inspected with different transducer types and high sensitivity to the chosen wave modes. From these results, the proposed ultrasonic guided waves method can be considered feasible for efficient detection and location of variety of defects in cylindrical geometry.

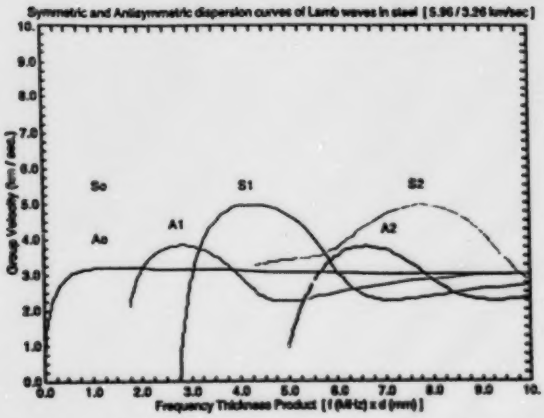


Figure 4 Group Velocity Dispersion Curves

EXPERIMENTAL RESULTS

In the following, tests were carried out on 1000x230x7.3 mm steel cylindrical geometry. Figure 5 shows the time response in terms of a sinusoidal waveform (RF radio frequency signal). These waveforms are measured using a fixed angle probe for the S_0 and A_1 modes in the pitch-catch arrangement. From the time response measurement (Figure 5a) and comparing the theoretical with the calculated group velocities for the selected mode, it was confirmed that at this frequency-thickness combination only the S_0 mode is propagating along the tested area in the cylinder.

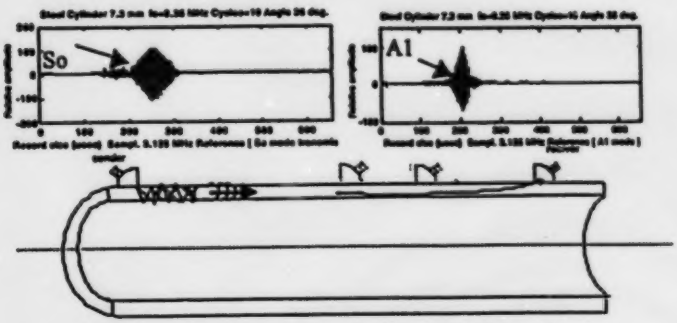


Figure 5 a) S_0 transmission mode b) A_1 transmission mode

Figure 5b illustrates the RF signal of A_1 mode. The experimentally calculated group velocity of this mode was equally equivalent to the theoretical group velocity obtained from the dispersion curves. The parameters used to excite these modes were used in most of the performed tests. They were selected from the calculated dispersion curves for given material properties (steel in our case) and optimized by the analyses of their wave structures. However, at this point we demonstrate that the selected modes can be excited and detected at considerable distances, results of the detected defect are presented in the following figures. It should be noted that for comparison reasons some of the following experiments were performed using EMATs probes where mode excitation is exercised

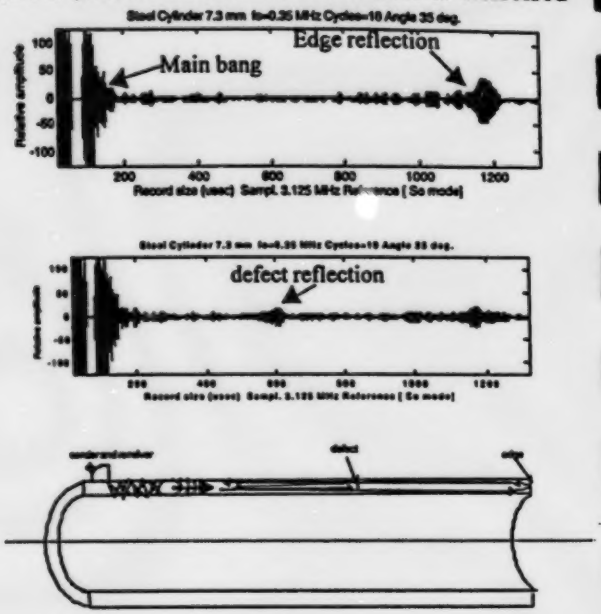


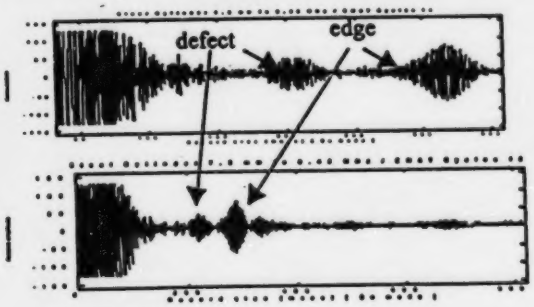
Figure 6 Pulse-echo response for cylinder a) without defect b) with defect

Figure 6 shows the time response obtained from the S_0 wave mode using the pulse-echo arrangement. We observe significant differences between the inspected area on the steel cylinder without defect (Figure 6a) and the inspected one with a 25x1.5x1.5 mm crack (Figure 6b). The time response shown in Figure 6a for a non-defected area of the cylinder shows only the S_0 mode reflected approximately at 1200μs (micro seconds) from the end of the specimen. Waves arriving before the S_0 wave mode represent the excitation (main bang) and the reverberation produced in the interface between the transducer element and the Plexiglas wedge. In Figure 6b, an additional wave packet corresponds to the reflection of the S_0 mode from the crack is observed. This reflection from the defect was confirmed by comparing the actual and calculated distance between the transducer and the defect. This distance is calculated from the product of time-of-flight measurement and the group velocity of the excited S_0 mode. An immediate conclusion from the time response for the pulse-echo arrangement

test is that we can directly see any changes in the time response waveform. Existence of an additional packet of waveform is a strong evidence of the existence of defect. Therefore, a guided wave pulse-echo propagates over long distances of these cylinders and can detect flaws along its path.

Figure 7a shows the results obtained from inspection of the same cylinder with previously detected defect using an EMAT probe to excite So wave mode in pulse-echo arrangement . Slight differences in the position of inspection probe and interpretation of the results are occurred because EMATs transducer transmits in both directions. In Figure 6a, EMAT transducer is placed faced to the defect resulting in an extra reflection of So time response. The first wave packet is the main bang exercised to excite the EMAT, the second wave packet represents a reflection produced from defect while third one is a reflection from the near end of the cylinder. For a longer time response (Figure 7b) we would be able to see another two reflections one after another. One is produced from the defect due to the reflection of the previously reflected wave from the near edge and the second is produced from the reflection of the secondly transmitted pulse from EMATs at the far edge of the cylinder.

Tests were continued on a half section cylinder whose ends were cut, giving a straight section 1000 mm long and sliced in the middle so that internal defects are easily introduced. The results in the following figures illustrate the detectability as well as the long range inspection capability of the guided wave procedure. Figure 9 shows results from crack-like defect detected at 190 mm away of EMAT transducer. Clear reflection from the defect is obtained as well as the near edge of the cylinder. In the second figure the transducer was placed on the other side of the cylinder so no reflection from the defect is observed. However, Figure 8 shows the reflection of the second far end of the cylinder.



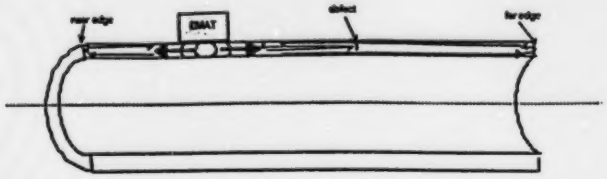


Figure 7 EMAT pulse-echo response for cylinder with crack-like defect

A number of tests were also carried out while the probe unit is scanned circumferentially to send its beam perpendicular to defects. In the following test, Figure 9 shows the time response obtained with the previously used So mode while using circumferentially pulse-echo approach to detect the same type of defects. Reflection of So mode from defect can now be clearly observed.

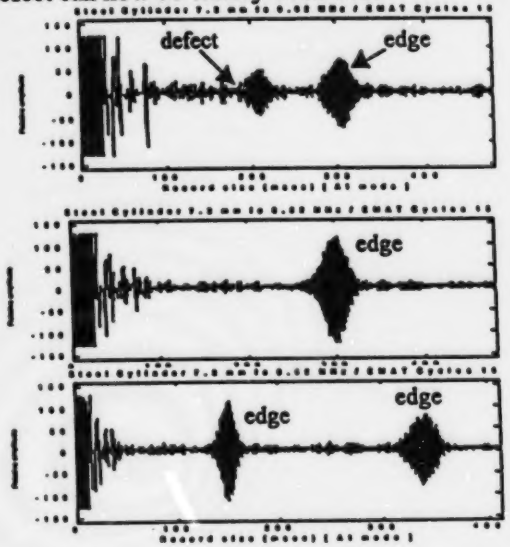
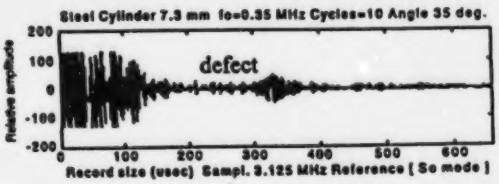


Figure 8 PE response for a steel cylinder a) with defect b) without defect c) two edge without defect



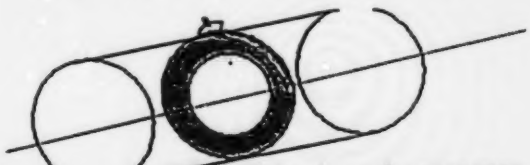


Figure 9 Circumferential pulse-echo response

CONCLUSIONS

To develop a global inspection technique which locates and detects defects in cylindrical structures, we have demonstrated the ultrasonic guided wave method as an appropriate and promising inspection technique. We showed how the ultrasonic guided waves method can be used as a highly sensitive, fast and cost effective inspection technique.

Under different conditions, several experimental tests utilizing So and A_1 modes with different frequency-thickness product were performed. Experiments showed that results can be repeated on different cylinders which is encouraging for adapting this technique to real time inspection. Yet our experimental conclusion on the sensitivity and applicability of using guided Lamb waves confirms that they can be used to inspect large areas in the axial and circumferential plane. Various modes can be induced and selected appropriately to optimize their propagation as a function of their selected characteristics. Sensitivity can be demonstrated from ability to detect, locate and validate structural damage in different type of cylindrical structures, also by demonstrating how ultrasonic guided wave method assesses different types of defects like fine surface-breaking flaws, crack-like defects, holes as well as wall thinning.

ACKNOWLEDGEMENT

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REFERENCES

[1] Meeker T.R and A.H. Meitzler,"Guided Wave propagation Elongated Cylinders and Plates," Physical acoustics, Vol. 1 Part A, 1964, pp. 111-167.

[2] Zemmanek J.JR. , "An Experimental and Theoretical Investigation of Elastic Wave Propagation in a Cylinder," The JASA, Vol. 52, No. 1 (part 2), 1972, pp. 265-283.

[3] Moher W. and P. Holler, "On Inspection of Thin Walled Tubes for Transverse and longitudinal Flaws by Guided Ultrasonic Waves," IEEE Transactions on Sonics and Ultrasinics, Vol. SU-23, 1976, pp. 369-374.

[4] Gazis, D.C., 'Three Dimensional Investigation of the Propagation of Waves in Hollow Circular Cylinders I. Analytical Foundation," Journal of the Acoustical Society of America, Vol. 31, No. 5, 1959a pp 568-573.

[5] Gazis, D.C., 'Three Dimensional Investigation of the Propagation of Waves in Hollow Circular Cylinders II. Numerical Results," Journal of the Acoustical Society of America, Vol. 31, No. 5, 1959a pp. 573-578.

[6] Silk M.G. and K.F bainton,"The Propagation Metal Tubing of Ultrasonic Wave Mode Equivalent to Lamb Waves," Ultrasonics, Vol. 17, 1979, pp. 11-19.

[7] Avioli M., "Lamb Wave Inspection for Large Cracks in Centrifugally Cast Stainless Steel," EPRI report Georgtown University 1988.

[8] Joseph L. Rose Dale Jiao and Jack Spanner, Jr. "Ultrasonic Guided Wave NDE for Piping," Material Evaluation November 1996.

APPENDIX B

Non-Destructive Evaluation of Compressed Gas Cylinders Using Guided Waves and EMATs

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NONDESTRUCTIVE EVALUATION OF COMPRESSED GAS CYLINDERS USING GUIDED WAVES AND EMATS

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Nondestructive Evaluation of Compressed Gas Cylinders using Guided Waves and EMATs

1. THE OBJECTIVE

The objective of this project was to determine the detectability of defects in the end sections of cylinders used to store compressed gas. Defects in the tangent sections were also examined.

2. THE SAMPLES

Two calibration samples and four full cylinders were provided for evaluation. The calibration samples were short end sections from the top and bottom ends of cylinders. The four full cylinder available for testing are listed below in Table 1.

Table 1. Inspected gas cylinders

ID	Cylinder SN	Inspection Date	Size
1	5880810	06/02/99	50L
2	6001607	06/02/99	50L
3	5848407	06/02/99	50L
4	6001583	06/02/99	50L

3. THE APPROACH

Tests were conducted on steel cylinders with real and simulated defects. A couplant-free EMAT probe was specially designed and mounted on the inspected cylinders. Results from the guided wave inspection technique demonstrated good detectability of defects in longitudinal and circumferential directions of the cylinders.

4. TEST PROCEDURE

Tests were carried out using EMAT probes tuned to excite the A_o Lamb wave mode in the cylinders at 0.426 MHz.

5. TEST SETUP

The propagation velocity of individual guided modes, once known, can be used to identify reflections from defects and their position. In our procedure this measurement is achieved using time-of-flight readings. Defects then are located by calculating the distance from the ratio of velocity of the propagated wave (group velocity) and the measured time-of-flight from the obtained reflections.

Tests were made in a pulse-echo setup using one transducer as transmitter and receiver of the guided wave. Thus, the inspected area with this setup is along a line between the transducer and the end edge of the cylinder.

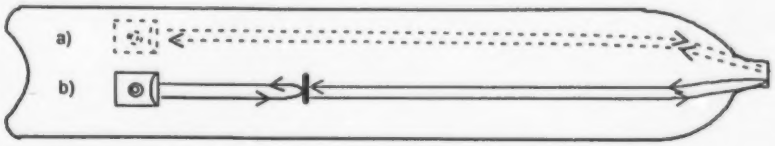

Figure 1 Pulse-echo setup a) without defect b) with defect #1

6. TEST RESULTS

Tests were conducted on 4 gas cylinders and two calibration sections of gas cylinder. These specimens were provided by TISEC for evaluation of the proposed guided wave inspection method. Using the samples provided by TISEC, a number of tests were carried out while an EMAT probe unit was scanned circumferentially to send its beam in the longitudinal direction along the cylinders (Figure 1).

Calibration Sample – Bottom End

Figure 2 shows the time response obtained from a 1"x.0.015"x (10% of the wall thickness) circumferential defect using a guided wave mode while scanning in pulse-echo to detect defects in the bottom end section of a calibration cylinder. Reflection of the guided mode from defect can be clearly observed after the main bang.

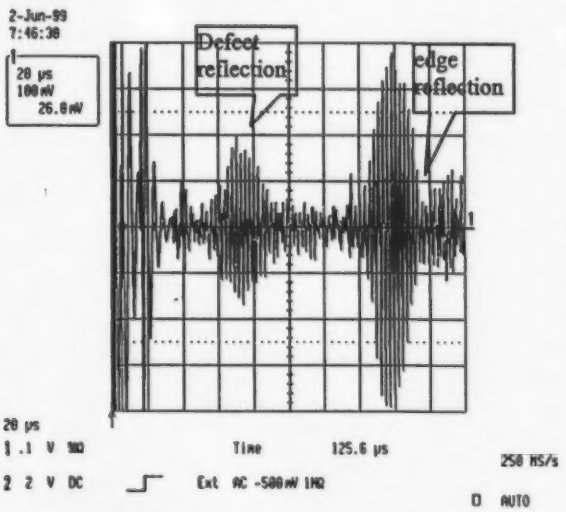

Figure 2 Response of 1"x.0.015"x(10% of the wall thickness) circumferential defect

The similar response from a 1"x.0.015"x (5% of the wall thickness) circumferential defect is shown in Figure 3.

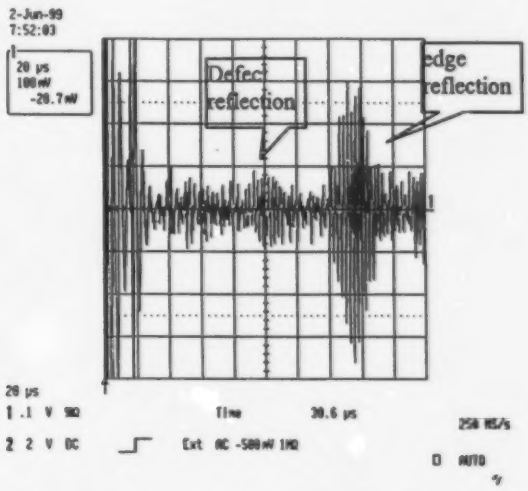

Figure 3 Response of 1"x.0.015"x (5% of the wall thickness) circumferential defect

Figures 2 and 3 demonstrate the detectability of these defects and show the raw signals. There are several ways to improve the signal-to-noise ratio including signal averaging. Figures 4 to 6 show the effects of averaging.

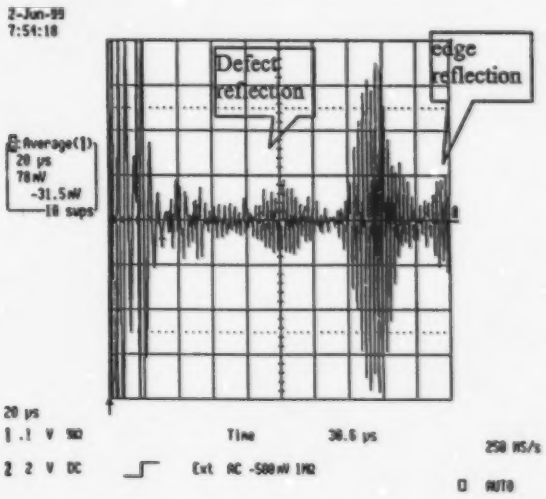

Figure 4 Response of 1"x.0.015"x(5% of the wall thickness) circumferential defect – Averaged 10 RF scan

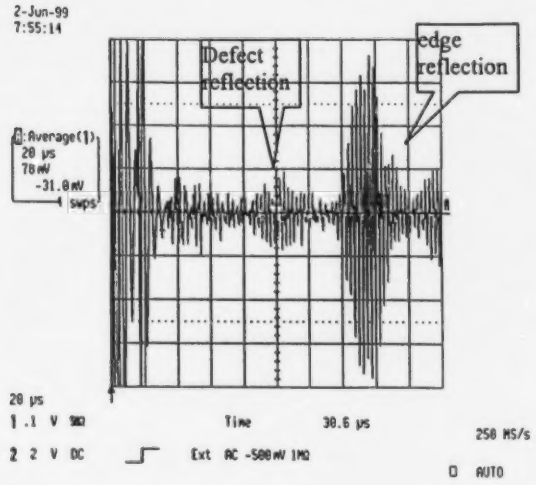

Figure 5 Response of 1"x.0.015"x(5% of the wall thickness) circumferential defect – Averaged 4 RF scan

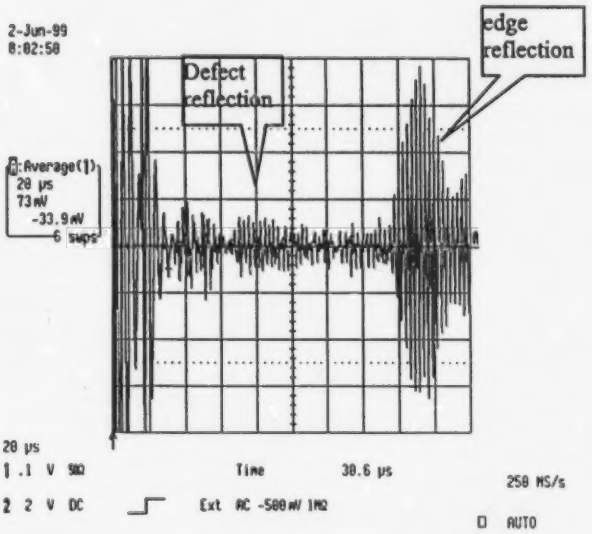

Figure 6 Response of 0.25"x.0.015"x(5% of the wall thickness) circumferential defect – Averaged 6 RF scan

Calibration Sample – Top End

The calibration cylinder (top end) was inspected with the same setup. However, no indications were detected.

Cylinder qualification test results

The same setup and procedure was used to identify and compare the results obtained from real defects in four gas cylinders. Table 2 summarizes some test results and remarks on the condition of the inspected cylinders.

Table 2. Inspected gas cylinders

ID	Cylinder SN	Inspection Date	Size	Results
1	5980810	06/02/99	50L	Indication
2	6001607	06/02/99	50L	Pass
3	5848407	06/02/99	50L	Pass
4	6001583	06/02/99	50L	Pass

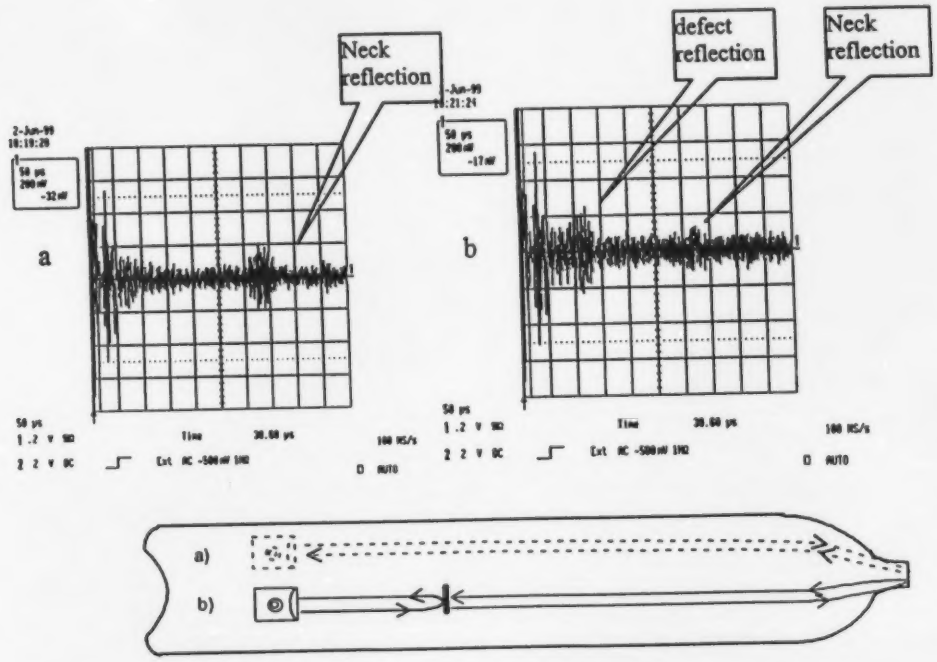

Figure 7 Pulse-echo setup a) without defect b) with defect

Figure 7 shows clear indications from a defect found in cylinder #1. This defect was found on the straight section of the cylinder. Indications were repeatable from two sides of the cylinder. On the other three cylinders no major indications were detected. Figure 8 shows a sample A-scan where no anomalies or reflections are obtained.

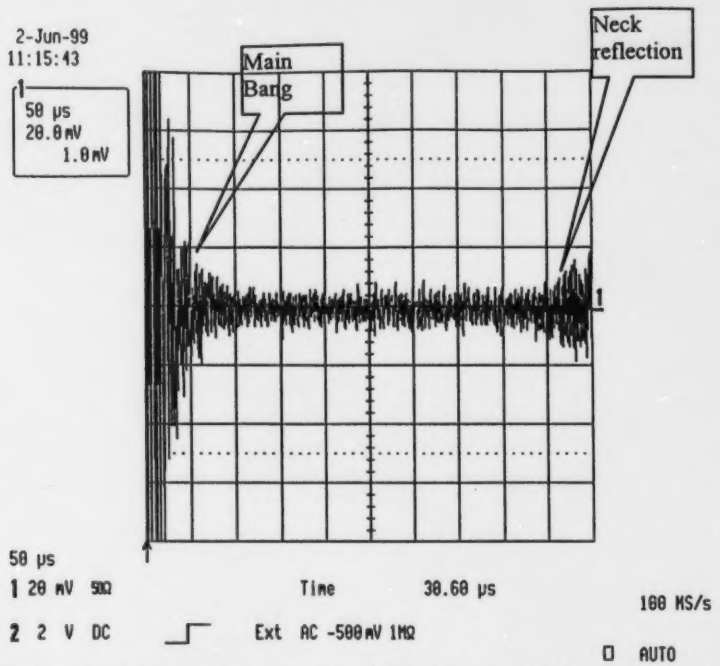

Figure 8 A-scan response of cylinder #2, no defects were detected

Figure 8 shows an inspected area where the probe is aligned in the axial direction; there no anomaly is observed, only the excitation (main bang) and the reflection from the end of the cylinder can be seen.

7. CONCLUSIONS

Detectability tests for detection of crack-like and wall thinning defects in gas cylinders demonstrated promising and repeatable results on different cylinders. These tests were performed with transducers available at Tektrend with specifications suitable for feasibility analysis. These inspection procedures can be substantially improved using transducers tuned to the specific tube geometry (wall thickness) and by optimizing the equivalent circuit of the transducer and detection instrumentation.